



Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery



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HIGHLIGHTS

- This review article focuses on engine exhaust waste heat recovery works.
- The organic Rankine cycle is superior for low to medium exergy heat sources.
- Working fluid and expander selection strongly influence efficiency.
- Several authors demonstrate viable systems for vehicle installation.

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ABSTRACT

Escalating fuel prices and future carbon dioxide emission limits are creating a renewed interest in methods to increase the thermal efficiency of engines beyond the limit of in-cylinder techniques. One promising mechanism that accomplishes both objectives is the conversion of engine waste heat to a more useful form of energy, either mechanical or electrical. This paper reviews the history of internal combustion engine exhaust waste heat recovery focusing on Organic Rankine Cycles since this thermodynamic cycle works well with the medium-grade energy of the exhaust. Selection of the cycle expander and working fluid are the primary focus of the review, since they are regarded as having the largest impact on system performance. Results demonstrate a potential fuel economy improvement around 10% with modern refrigerants and advancements in expander technology.

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1. Introduction

The Internal Combustion Engine (ICE) has been a primary power source for automobiles, long-haul trucks, locomotives, and ships over the past century. Over this time, periods of high fuel costs and concerns about foreign oil dependence have resulted in increasingly complex engine designs to decrease fuel consumption. For example, engine manufacturers have implemented techniques such as enhanced fuel/air mixing, turbocharging, and variable valve timing in order to increase thermal efficiency. However, around 60–70% of the fuel energy is still lost as waste heat through the coolant or the exhaust [1]. Moreover, increasingly stringent emissions regulations are causing engine manufacturers to limit combustion temperatures and pressures lowering potential efficiency gains.

To date, legislation of exhaust emission levels has focused on carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). Manufacturers of Spark Ignition (SI)

engines have met these standards by using the Three Way Catalyst (TWC), while Compression Ignition (CI) engines have been fitted with a 4-way aftertreatment system [2]. In both cases, catalytic devices convert harmful emissions to nitrogen gas (N₂), carbon dioxide (CO₂), and water (H₂O). Through modification of injection timing and rate shaping, CI engines often operate with reduced combustion temperatures to prevent the formation of NO_x as its conversion in a 4-way aftertreatment system is relatively difficult. SI engines often accomplish a similar tactic by retarding the spark timing; however, TWC devices have the inherent advantage of using CO and HC to reduce NO_x. Therefore, there is less of a need to adjust the combustion timing. As mentioned previously, these strategies reduce engine efficiency by achieving less combustion at prime crank angles.

It appears that future regulations will focus more on CO₂ emissions, which require increasing the efficiency of the ICE or moving to more costly hybrid drivetrains [3]. Of interest, many researchers recognize that Waste Heat Recovery (WHR) from engine exhaust has the potential to decrease fuel consumption without increasing emissions, and recent technological advancements have made these systems viable and cost effective [4].

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The two primary sources of waste heat from an ICE are the engine exhaust (medium-grade) and engine coolant (low-grade). Other options for heat recovery include the relatively smaller amounts available from an Exhaust Gas Recirculation (EGR) cooler and Charge Air Cooler (CAC) [2]. Despite both primary sources having similar energy content, the higher temperature of the engine's exhaust makes it more thermodynamically attractive when viewed from the perspective of exergy. This results in a higher theoretical efficiency gain when coupled to a heat engine [1]. Previous research in this field involves the recovery of each source, as well as the potential for simultaneous heat recovery from both the engine coolant and exhaust. Most studies choose a Rankine cycle for WHR due to its simplicity and ability to operate with low to moderate temperature differences [5].

1.1. Rankine cycle

A Rankine cycle is a closed-loop system where a working fluid repeatedly circulates through four components to transform waste heat into mechanical or electrical power. If the selected working fluid is organic in nature, researchers often refer to this system as an Organic Rankine Cycle (ORC). The first step in this cycle uses engine exhaust to heat the fluid in an evaporator in order to capture waste heat available (process 2–3 in Fig. 1a). Selection of the evaporation process as the first step has been made in order to illustrate the conversion of waste heat to usable energy; however, the choice is otherwise arbitrary since the system is cyclic (thermodynamic textbooks primarily indicate the beginning of this process with the “2” nomenclature). The superheated vapor then passes through an expander to generate mechanical or electrical power; this device can be either a displacement or a turbomachine (process 3–4 in Fig. 1a). After the fluid undergoes expansion, it flows through a condenser in order to discharge low-grade thermal energy to the atmosphere (process 4–1 in Fig. 1a). Finally, a pump compresses the working fluid back to its original state (process 1–2 in Fig. 1a). To note, there are two variations of the traditional Rankine cycle; reheat and regenerative.

In the reheat version, the working fluid does not expand fully to the condenser pressure in a single stage (process 3–4 in Fig. 1b). Instead, the cycle sends the partially expanded working fluid back to the evaporator for reheating (process 4–5 in Fig. 1b) with a subsequent a second expansion resulting in the working fluid ending at the condenser pressure (process 5–6 in Fig. 1b). The principle advantage of the reheat Rankine cycle is an increased quality at the expander exit [6]. A higher working fluid quality indicates a reduction in moisture content, which increases the lifetime of turbine expanders. In the regenerative variation, a portion of partially expanded working fluid (process 5–6 in Fig. 1c) preheats the condensed liquid before it enters the boiler (process 2–3 in Fig. 1c). Preheating in this manner decreases the amount of heat added at low temperatures, increasing the mean effective temperature of heat addition while enhancing cycle efficiency [7]. Of pertinence, these explanations only apply to traditional steam Rankine cycles, not to ORC's; however, it is important to understand the fundamentals of these cycles before expansion to ICE utilization. Fig. 1 provides a comparison of the three Rankine cycle variants for clarity of description.

1.2. Alternative WHR methods

It is also possible to achieve WHR using other unique thermodynamic cycles. One such method is the open Brayton cycle, which requires only three components. Another common option is the Stirling cycle engine that includes a closed system comprised of

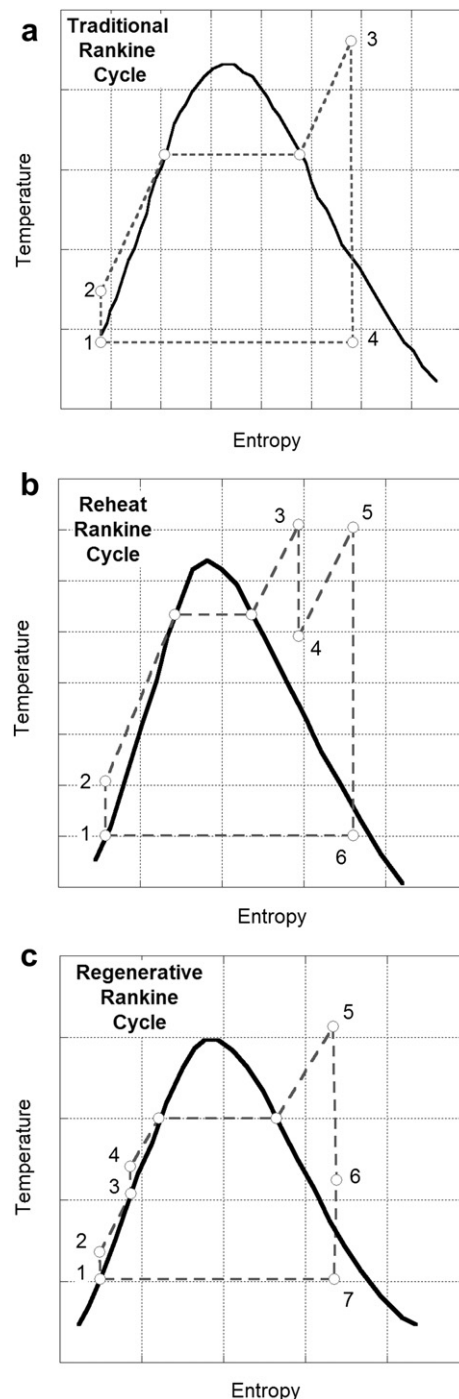


Fig. 1. Variations of Rankine cycle: (a) Traditional, (b) reheat, and (c) regenerative [7].

a regenerator and a cylinder, which contains both a displacement and power piston [8]. More recently, increased focus has been placed on the development of Kalina cycle systems, which parallels an ORC in configuration with the addition of an absorber and flash tank [9]. This cycle uses a variable composition mixture of ammonia and water as the working fluid. Similarly, supercritical carbon-dioxide systems have drawn attention in various WHR applications. While most WHR research focuses on thermodynamic cycles, thermoelectric (TE) devices offer a unique alternative, since they directly convert thermal energy into electrical energy.

1.3. WHR comparison

As previously elucidated, an ORC is the focus of most small-scale WHR efforts due to its simplicity and ability to operate efficiently between small to moderate temperature differences. Another primary advantage of the ORC is the use of widely available and affordable components because of the similarities between ORC and refrigeration systems. While no single WHR method is superior for every system size and waste heat source, the authors believe ORC's provide an attractive combination of efficiency and affordability for engine exhaust WHR. Some selected research efforts on alternative WHR methods are described in the following paragraphs simply to provide context and starting references for the reader, since an exhaustive comparison is outside the scope of this paper. Additional resources on Kalina cycles [10–13], thermoelectrics [14–16] and carbon dioxide transcritical cycles [17–19] are available.

By contrast, relevant studies have found that various Brayton cycles are marginally attractive as an alternative to turbo-compounding [20]; however, they require a longer payback time [21], and are less attractive for low to medium temperature WHR [22]. Similarly, Kubo found that several Stirling cycle configurations to recover waste heat from an adiabatic diesel engine were not economically attractive [8], and fail to match previous performances of ORC [23] and steam Rankine cycle [24] systems. More recently, the ORC investigated by Bianchi and De Pascale was favored over the Stirling engine [22]. Kalina cycle research has focused primarily on large-scale facilities, demonstrating that these systems efficiently recover waste heat in the engine exhaust temperature range [9,25–28]. Practical restrictions on maximum cycle pressure suggest that carbon dioxide transcritical cycles would not be feasible for exhaust WHR, despite the cycle's favorable performance shown by Chen at low temperatures [29].

A summary of the present and future applications of thermoelectric devices is provided by Riffat and Ma, defining their maximum temperature difference as 70 °C and efficiency at around 5% [30]. Even with cascading devices, which will function for differentials of 130 °C, the authors restrict the competitive regime of TE's to low temperature waste heat. If efficient WHR is not required to achieve the objective, such as meeting the electrical requirements of a family car, TE's could provide a viable alternative to ORC systems [31].

The next section will focus on a historical review of ORCs for WHR and power generation. Of importance, in addition to ICE waste heat, Najjar recognizes the possibility of using ORC's for WHR from other power generating devices, such as gas turbines [32]. More recently, Quoilin and Lemort described the use of ORC's as part of several green energy systems [33]. Among these were biomass, solar, and geothermal stations. Both works include descriptions of previous publications in their respective research areas. However, the primary goal of the authors is to increase the thermal efficiency of the ICE for lower greenhouse gas emissions without adversely influencing emissions. Of interest, there has been research on using recovered exhaust waste heat for automobile heating, offering a secondary avenue of usage [34].

2. WHR review

In 1973, Morgan et al. were among the first to study the application of an external combustion Rankine engine in an automotive application [35]. Concerns about the ability of ICE's to meet the Clean Air Act mandated emission levels for 1976 motivated these researchers to investigate alternatives to traditional combustion engines. As a result, the group evaluated the potential of an ORC system as they recognized that separating the combustion process

from the power cycle creates an inherent emissions advantage. Since an engine's emissions are contingent on the combustor geometry and its operation, optimization of the combustor design separately can minimize emissions, regardless of power extraction concerns. In order to determine whether sufficient power output was possible required the creation of computer models and a regenerative Rankine engine prototype.

The group used a 145.5 hp expander output for component sizing and determined the system would fit within a 1972 Ford Galaxie engine compartment with only minor modifications. They selected Fluorinol-85, 85% tetrafluoroethanol and 15% water by volume, as the working fluid because of a low freezing point (−82 °F), good thermal stability, nearly isentropic saturated vapor line, and acceptable cycle efficiencies for boiler temperatures of 500–625 °F. The prototype used a radial firing burner integrated with the vapor generator to evaporate the working fluid that generated power within the expander. Tests using a single and four-cylinder (V-4) expander found that the single cylinder expander exhibited superior efficiency. They observed good agreement between computer models and prototypes and concluded that an 11% fuel economy improvement was achievable based on 400 h of testing utilizing a 5.5 hp system at Thermo Electron Corporation (TECO).

Three years later, Patel and Doyle documented the first application of using an ORC for engine WHR [36]. Their system used the exhaust waste heat of a Mack 676 diesel engine installed in a long haul truck by coupling the turbine pinion gear to the PTO with a speed reduction gearbox. While small vehicles with ICE's have potential for efficiency gains, the authors cite extended periods of near constant engine speed operation and high yearly mileage as reasons long haul trucks are more attractive for ORC applications. To minimize irreversibility, the group used Fluorinol-50 as the cycle working fluid in an attempt to minimize the temperature difference between the working fluid and engine exhaust. In specific, they operated between 650 °F at turbine inlet and 158 °F at condenser exit.

The constructed prototype used a vapor generator as part of the exhaust stack, a condenser combined with the existing truck's radiator, and a three-stage axial flow turbine expander. Figures within their report illustrate that the ORC components were readily configured within the truck's engine compartment. Subjecting the ORC equipped truck to a NAPCA control route demonstrated a 13% increase in maximum power output along with a 15% improvement in fuel economy. Moreover, this performance slightly exceeded model predictions at all power levels and speeds tested. They conclude that the \$3000 ORC system could pay for itself with fuel savings in less than one year with 150,000 miles of travel at the current fuel cost of \$0.45 per gallon.

Continuing the collaboration between TECO and Mack Trucks, Patel et al. describe plans for a yearlong single vehicle test of the ORC equipped model F7865T tractor in FY 1979 [37]. This paper also documents a planned expansion of the system for ten trucks in the FY 1981–1982; however, no further information exists on the planned expansion. Using the previously determined 15% fuel consumption decrease, they mention saving 3120 gallons of fuel for every 100,000 miles traveled by the truck.

In 1981, Hall summarizes the increase in cogeneration, which he describes as the generation of energy from the excess energy supplied during another process [38]. This necessity stems from the 100% OPEC inspired price hike on oil, which made it less expensive to save a Btu than to generate an additional one. While concerns about the substantial capital investment still existed at the time of the paper, Hall contends that installation of cogeneration systems is not overly complex.

In the same year, Heywood provides a review of the status of conventional engines as compared to alternative versions [39].

During this time in the literature, the efficiency improvement potential of direct-injection and turbo-compounded diesels were being tested for future incorporation. The alternative systems identified by Heywood were gas turbine systems, Stirling engines, and Rankine cycle engines. This paper describes the advantages and disadvantages of each system; however, he did not intend the study to be definitive because of rapidly changing constraints. Of interest, Heywood acknowledges using an ORC for WHR as a possible method for further efficiency improvements over turbo-compounded diesels.

Also in 1981, Marciniak compares the suitability of seven different working fluids for Rankine cycle systems [40]. The fluids considered were water, methanol, 2-methyl pyridine/water, Fluorinol-85, toluene, Freon R-11, and Freon R-113. This working fluid evaluation occurred for 600–2400 kW industrial applications with waste heat temperatures between 500 and 1100 °F. Marciniak makes these working fluid recommendations after studying their thermo-physical properties, system performance and size, environmental impact and safety, various capital and operating costs, and potential return on investment. He does not exclude any of the potential working fluids due to health or safety risks, believing these concerns were manageable through a careful system design. Under high temperature conditions, thermal stability concerns eliminated methanol and both Freon refrigerants from consideration. From an economic standpoint, this paper provides the estimated capital cost versus power output for the distinctive working fluids. As power output increases from 800 kW to 2400 kW, typical Rankine system costs are shown to exponentially decay from around \$1000/kW to \$600/kW. The least expensive system utilized water, followed by toluene, 2-methyl pyridine/water, and Fluorinol-85.

In the next year, Poulin et al. conduct a similar evaluation in running a steam Rankine cycle system off several adiabatic diesel configurations [24]. They simulate this system using turbocharged non-aftercooled (TC), turbocharged aftercooled (TC/A), turbocharged turbo-compound non-aftercooled (TCPD), and turbocharged turbo-compound aftercooled (TCPD/A) engines. They find a maximum brake specific fuel consumption (BSFC) improvement of 16.2% for the TC diesel with lesser improvements for the other configurations. They conclude that the payback time including maintenance would be 2.3 years, making the system economically attractive to the end user.

Also in 1984, Italian research in the field of ORC's was described by Angelino et al. [41]. This review of the authors' works includes 14 ORC engines with power outputs between 3 and 500 kW, and maximum operating temperatures between 70 and 340 °C. Of the studies featuring higher maximum cycle temperatures, high molecular weight wet (negative saturated vapor curve slope) fluids are used to generate power through multi-stage turbines. While relatively few cycle efficiency results are presented, the authors show a small increase in performance as the working fluid's molecular weight increases.

By 1985, increased interest in simulating ORC's led Badr to develop correlations for thermophysical properties of many of the period's refrigerants [42]. Badr bases these correlations off works by Martin [43] and Downing [44], while showing good agreement with the limited data available. This effort provides equations that can fit directly in a model for a working fluid's saturation pressure, specific volume, specific enthalpy, and specific entropy. Of importance, the correlations hold for each refrigerant as a saturated liquid, saturated vapor, and superheated vapor.

Badr publishes another paper in the same year describing the working fluid selection process for a low power output (<10 kW) Rankine cycle engine operating between 40 °C and 120 °C [45]. This paper includes an evaluation of thermodynamic and physical selection criteria for 67 prospective working fluids, while identifying

three superior candidates. While none completely satisfied all the criteria, the short listed fluids were the fluorinated hydrocarbons R-11, R-113, and R-114.

After considering a turbine or displacement-type machine for the Rankine engine expander, Badr chose to use a multi-vane type displacement machine. At this time, single-stage turbines were inefficient for this application due to impractical optimum blade velocity. Moreover, the high cost of multi-stage turbines prohibited their inclusion. Computer modeling of the preferred fluids revealed R-11 exhibited the highest cycle efficiency; however, since R-11 has a relatively low thermal stability limit of 120 °C, this work concludes with R-113 as the best working fluid.

Also in 1985, Bailey performs a technical and economic study of three alternative power cycles for WHR from an adiabatic diesel engine, and compares each system's performance with a baseline turbo-compounding diesel [21]. The power cycles examined were a steam Rankine, ORC with RC-1 working fluid, and various Brayton cycles (including air Brayton). Bailey documents engine specific fuel economy improvements via computer models, which are in direct proportion to improvements in vehicle fuel economy [46]. Simulations show the largest fuel savings were possible with the RC-1 ORC, followed closely by the steam Rankine, with smaller improvements from Brayton cycle systems. The calculations were based on 100,000 miles of annual travel, with the RC-1 ORC providing a fuel savings of approximately 1400 gallons, the largest among the different options. At 1985 fuel price levels, the steam Rankine cycle has the shortest payback time at 3.2 years, followed by the RC-1 ORC and intercooled Brayton at around 4.1 and 4.7 years respectively.

Six years later, Badr elaborates on his 1985 paper by ranking types of low power output (5–20 kW) expansion machines for use in a steam Rankine engine configuration [5]. A Rankine cycle fits this application because it is able to achieve 60–70% of the Carnot limit for small temperature differences; whereas, it can only achieve up to 50–60% for large differentials in temperatures. He evaluates these devices for a combined heat-and-power (CHP) system, which involves the simultaneous production of electrical power and useful heat from a single generating power plant. A survey of previous research led the author to conclude that turbines and reciprocating expanders were not particularly suitable for a low power, low speed application. Badr concludes that a Wankel expander was best for the CHP system, slightly above a helical-screw expander.

Jumping ahead to 1993, Oomori and Ogino develop a Rankine cycle system that uses the waste heat from the engine coolant in a passenger car [47]. The authors chose not to recover the higher-grade waste heat found in the engine's exhaust because engine speed fluctuations complicate the control process. They select HCFC123 (hydrochlorofluorocarbon) as the working fluid for this application in order to allow liquid–vapor phase change within the authors' low temperature evaporator. Moreover, they replace the engine water pump with an ORC pump, while using the engine coolant passages as the evaporator, and the existing radiator as the condenser. They measure output from the scroll expander in order to determine the fuel economy improvement during bench testing and find only a 3% gain for an ambient temperature of 25 °C.

Two years later, Larjola evaluates prototype high-speed oil free turbogenerator-feed pumps in an ORC for WHR from a 425 °C source [48]. Instead of using the conventional separated configuration, the novel device directly couples the pump, turbine, and generator. Upon examination of several working fluids, toluene is chosen as the most suitable. The author notes the fluid's lower specific heat of vaporization and the possibility of using a single-stage turbine as advantages toluene has over water. This is further indicated in the results as a toluene-based ORC achieves 26% efficiency while a steam Rankine cycle manages only 11–19%.

In 1997, Hung compares the performance of six working fluids against water for use in a Rankine cycle for WHR of low-grade waste heat [49]. The candidate fluids were benzene, ammonia, R-11, R-12, R-134a, and R-113. Hung chooses water as the baseline fluid since it provides low Rankine cycle efficiency for waste heat sources below 370 °C; thus, a direct comparison of organic fluids to water justifies the use of organic fluids in low temperature applications. Determination of working fluid suitability is a function of the examination of molecular weight, saturated vapor line slope, turbine enthalpy drop, maximum stability temperature, and critical point as indicated in Table 1. This paper involves a modeling study in order to determine the maximum Rankine cycle efficiency for each fluid at different turbine inlet temperatures. As shown in Fig. 2, benzene has the highest efficiency of the investigated fluids in spite of having a relatively high latent heat at low pressure. In general, the larger latent heat working fluids result in inefficient operation since the condenser rejects much of the fluid energy. In addition, for given evaporator and condenser temperatures, higher critical temperature working fluids exhibit superior first-law efficiencies in an ORC.

Hung follows up this earlier work four years later by examining the potential of five different dry fluids (fluids with a positive slope on their T - s diagram saturated vapor curve) to perform WHR in an ORC [50]. This investigation includes three hydrocarbons and two refrigerants as follows: benzene (C_6H_6), toluene (C_7H_8), p -xylene (C_8H_{10}), R113 and R123. Using a 10 MW waste heat source at 600 K, Hung finds that p -xylene exhibits the lowest irreversibility of the prospective fluids. Another study, using a constant 15 °C temperature difference between the turbine inlet and waste heat source, shows that p -xylene provides the highest cycle efficiency. The refrigerants perform relatively better with decreasing source temperature; however, using these relatively expensive fluids in a large system would add significant cost.

In 2003, Kane et al. propose creating a small hybrid power generator utilizing WHR for remote locations [51]. This station would recover thermal energy from solar collectors and a diesel engine while creating electricity through two superimposed ORC's. This design allows power generation during cloudy periods and at night via WHR from the engine block coolant and exhaust gas. The ORC's involve a topping cycle with HCFC-123 and a bottoming cycle using HFC-134a with power generation through a separate scroll expander unit. While a single definition of topping and bottoming will not apply to all the papers reviewed here, in general, a topping cycle will convert waste heat to mechanical or electrical energy; whereas, a bottoming cycle redirects the waste heat to a useful heating process. Earlier in this paper, Khalifa indicates the nomenclature of a bottoming cycle in reference to a Brayton cycle generating power from engine exhaust waste heat. For Kane et al.'s paper, the authors associate the topping cycle with the higher exergy source (exhaust heat) and the bottoming cycle with the lower exergy sources (engine coolant and heat rejected from topping cycle condenser). To test efficiency, they ran three series of tests using the station including limited testing made in situ with the fully integrated system. Results show an overall cycle efficiency of $14.1 \pm 0.2\%$ with the performance deemed satisfactory for relatively low temperatures (up to 165 °C) and low power ranges (up to 10 kW).

In the next year, Liu et al. conduct an analysis of working fluid selection on the performance of an ORC for WHR [52]. They model a simple ideal Rankine cycle in order to study the thermal efficiency of the system and total heat-recovery efficiency for various working fluids utilizing low-grade energy sources. For completeness, the authors choose to evaluate wet, dry, and isentropic fluids in the study. The authors determine that hydrogen bonding in water, ammonia, and ethanol results in wet fluids that are inappropriate for a low temperature ORC process. Simulation results predict that thermal efficiency is a weak function of the critical temperature of the fluid and lower critical temperature fluids provide less efficient heat recovery.

In the same year, Schmid examines potential CO₂ emissions reductions by utilizing WHR on marine engines [53]. Since these engines achieve around 50% thermal efficiency along with the typical tradeoff between efficiency and NO_x emissions, the author cites WHR as a more promising avenue for CO₂ emission reductions than engine redesign. Schmid proposes a heat recovery plant that generates electricity using a steam turbine and power turbine in order to drive a turbo-generator. Their calculations indicate that the operation of the heat recovery plant by means of a 68,640 kW Sulzer 12RTA96C engine results in a 12% gain in overall efficiency. Because the estimated payback time was only four years, the manufacturer went ahead and installed the complete heat recovery plant on some ships in the manufacturer's fleet [54].

In 2005, El Chammas and Clodic propose an ORC for WHR from the cooling circuit and exhaust of a 1.4-L spark ignition engine within a hybrid vehicle [4]. With this configuration, conversion of mechanical turbine rotation to electrical energy with a generator allows subsequent storage in a battery pack for later use by an electric motor. The authors examine eight working fluids (water, isopentane, R-123, R-245ca, R-245fa, butane, isobutane, R-152a) for use in a Rankine bottoming cycle. The simulation results in Fig. 3 utilize a condensing temperature of 55 °C while indicating that water provides the highest cycle efficiency, followed by R-123, isopentane, and R-245ca. In spite of R-123 resulting in efficient operation, the authors note the fluid is an HCFC and thus unsustainable for environmental reasons.

Their efforts find that dry or isentropic fluids achieve similar or lower efficiencies with increasing superheat at the turbine inlet, while the cycle efficiency increases for wet fluids such as water. Rankine cycle efficiency does increase for higher operating pressures; however, they mention that manufacturers must weight these benefits against the associated cost increase. A comparison of possible Rankine cycles, including a high-pressure steam Rankine cycle (HPSRC) and low-pressure steam Rankine cycle (LPSRC) show that the HPSRC had the highest actual efficiency as indicated in Table 2. In particular, HPSRC offers a 12–27% fuel economy improvement depending on engine speed and load, while the two favored organic fluids (isopentane, R-245ca) present a 17–32% improvement when used in an ORC. Additional exhaust backpressure introduced by the boiler dampens this performance increase, resulting in a horsepower loss of 1.5–2.5% at high loads and 0.2–0.5% at low loads.

In 2006, Stobart and Weerasinghe review and compare six previous WHR efforts for SI and CI engines with a summary of the

Table 1
Thermophysical working fluid properties [49].

Parameter	H ₂ O	NH ₃	Benzene	R134a	R12	R11	R113
Molecular weight	18	17	78.14	102	121	137	187
Saturated vapor curve slope	Negative	Negative	Positive	Isentropic	Isentropic	Isentropic	Positive
Critical point	647 K 22.06 MPa	405.3 K 11.33 MPa	562.2 K 4.9 MPa	374.15 K 4.06 MPa	385 K 4.13 MPa	471 K 4.41 MPa	487.3 K 3.41 MPa
Latent heat at 1 atm (kJ/kg)	2256.6	1347	438.648	215.52	166.1	178.8	143.9
Max. stability temperature (K)	None	750	600	450	450	420–450	450–500

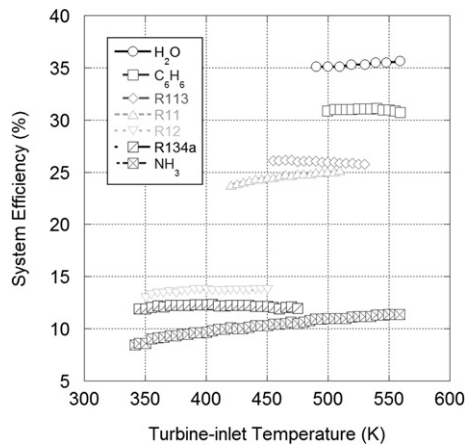


Fig. 2. Variation in system efficiency for various working fluids [29].

Table 2

Comparison of Rankine cycles [4].

Parameter	HPSRC	LPSRC	ORC-R245ca	ORC-isopentane
Net electrical output (kW)	5	5	5	5
Ideal efficiency (%)	22.7	15.3	15.8	16.3
Actual efficiency (%)	13.3	8.9	8.7	9.0
Max pressure (bar)	25	8	22.5	19
Max temp. (°C)	260	220	143	151
Mass flow rate (g/s)	15.2	22.7	241	121

Also in 2006, Leibowitz et al. highlight the advantages of using screw expanders over turbines in small (20–50 kW) ORC's by considering both cost and performance [57]. At these sizes, the authors note the high rotational speeds of turbines require high ratio gearboxes and expensive lubrication systems. Of the different types of expanders, twin-screw type machines are identified as the most promising, citing their ability to operate at higher rotational speeds than vane, scroll, or reciprocating expanders. Consisting of a pair of meshing helical rotors, recent development of the "N" profile has improved the screw expander's performance by up to 10%. Furthermore, the twin-screw expander provides efficiencies around 70% during low speed operation (1500–1800 RPM), resulting in acceptable performance during periods of decreased waste heat supply. Cycle simulations showed an 8.5% increase in total power output by recovering exhaust heat from a gasoline engine generator at a cost of \$1500–1800/kW.

Colonna and van Putten publish a two-part effort in 2007, describing a dynamic power cycle simulation software package called SimECS [58,59]. This software uses conservation (mass, momentum, energy) and constitutive (heat transfer coefficients, fluid properties, fluid dynamic correlations, rate of reaction) equations in order to describe the complete system. The use of bilateral coupling and the causality principle leads to a solvable system of low index algebraic and differential equations (DAEs). Validation of the software occurs through steady state and dynamic simulation of a 0.6 MW steam Rankine system in the second part of the work. Results indicate a maximum discrepancy of 6% between Cycle-Tempo and SimECS computer simulation models. These works present a highly accurate method of modeling WHR systems during normal and off-design condition operation, representing one of the first detailed treatments of transient cycle simulation.

In the same year, Wei et al. investigate the performance of an ORC system during steady operation and under disturbances [60]. Exhaust from a gas turbine (610–650 K) acts as the waste heat source driving the cycle, which uses R-245fa as the working fluid and a separate turbine to generate power. This work validates cycle simulations on a 100 kW system through obtained experimental data, ensuring accurate model predictions. Optimization of the ORC performance suggested small sub-cooling (0.5–0.6 K) at the condenser outlet leads to the maximum WHR system output.

In this study, the authors quantify the effect on cycle performance of variations in exhaust mass flow rate, exhaust inlet temperature, air mass flow rate, and ambient temperatures. These simulations show linear increases in output power and efficiency for increasing exhaust mass flow rate, increasing exhaust inlet temperature, and decreasing ambient temperature. They observe a 30% decrease in output power from typical winter temperatures as compared to those of summer because of the higher cold sink temperature. Finally, the exergy destruction rate of the evaporator is the largest of all the ORC components in the cycle.

Also published in 2007 is a two-part effort by Teng et al. regarding WHR from heavy-duty diesel engines using an ORC [2,61]. The authors propose a hybrid energy system for 2010 versions of these engines in the first paper, consisting of a diesel

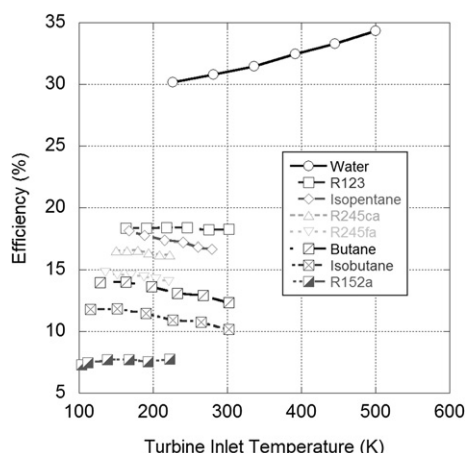


Fig. 3. Rankine cycle efficiency for various working fluids [4].

cycle hybridized with an ORC for WHR. Transient operating conditions commonly lead to selecting reciprocating expanders above turbines, since variable heat addition leads to wetness late in the expansion process and potential damage to turbine blades. The working fluid selected for the cycle is a dry fluid having a critical pressure under 70 bars. Both first and second law analyses reveal that WHR from engine coolant was unattractive due its respective low energy level; however, their investigation indicates that energy from engine exhaust, EGR, and the CAC is suitable. The authors provide a schematic of the proposed system, where they place an exhaust cooler downstream of a Diesel Particulate Filter (DPF). Their simulations indicate that the supercritical ORC system can potentially recover 55 kW from the waste heat (169 kW) via the three devices, increasing the output of the engine by 20% without additional fuel. A further benefit in their proposed cycle is achievable by decreasing the condenser size through utilizing heat from engine coolant.

Their second paper discusses the merits of various working fluids for their ORC-WHR system based on thermodynamic properties. This paper documents inorganic and organic fluids as both pure fluids and binary-mixture fluids. In specific, characterizations of these fluids happen as wet (water), isentropic (R134a), or dry (R245fa). Of these, the authors determine isentropic, slightly wet, or slightly dry fluids are generally most suitable for ORC-WHR systems. However, selection of the proper working fluid depends on the temperature range of the system; hence, no single fluid will be best for all applications. The authors also conclude a properly selected binary-mixture working fluid is capable of improving the thermal efficiency of the ORC by up to 15%.

In the same year, Mago et al. investigate the performance of low temperature ORC's with seven working fluids [62]. The fluids considered were R134a, R113, R245ca, R245fa, R123, isobutane, and propane. They compare the performance of each fluid against water in waste heat temperature ranges such as less than 380 K, 380 to 430 K, and greater than 430 K. As mentioned in a previous paragraph, water is not economical for waste heat levels below a temperature of 643 K. Fig. 4 presents the results of their efforts as a function of computer simulated ORC thermal efficiency with each fluid. This allows the researchers to make recommendations for each temperature range. In specific, the working fluid with the highest boiling point (R113) provides the highest efficiency, while they observe that the worst efficiency results from the fluid with the lowest boiling point (propane). This suggests that higher boiling point fluids work comparatively better in ORC's.

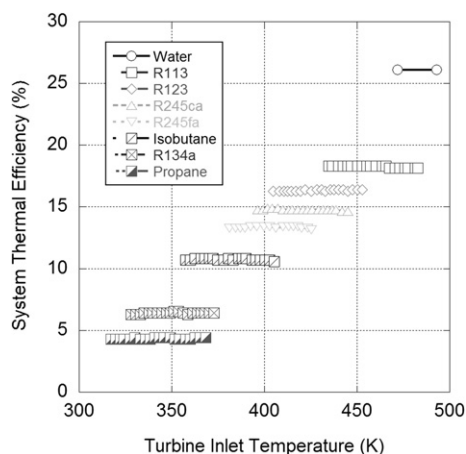


Fig. 4. Thermal efficiency of Rankine cycle with turbine inlet temperature for various working fluids [46].

This year additionally provides the efforts of Endo et al. with respect to their experimental results involving a steam Rankine system installed on a Honda Stream hybrid vehicle [1]. The WHR power cycle utilizes the waste heat from engine cooling and engine exhaust using an innovative catalyzed evaporation device that replaces the exhaust port of the engine. The system generates power from a swash plate axial piston type expander coupled to a generator. Electronic control of the generator load provides steam pressure regulation by imposing the rotational speed of the expander. The authors use feed-forward control of the steam flow rate in order to maintain the expander inlet temperature between 400 and 500 °C.

For proof of concept, they drive the vehicle in the EPA highway fuel economy test mode, Japanese 10–15 mode, and at constant driving speed of 100 km/h. They observe successful control of the system during broad and dramatic engine load changes, the first reported instance of such transient control capabilities. Experimental data shows the novel evaporator recovers 95% of the exhaust energy as steam and heat from the catalytic purification reaction, while the expander achieves a maximum of 13% thermal efficiency. In addition, results show a 13.2% increase in thermal efficiency relative to the base vehicle, leading the authors to conclude that the Rankine system is an effective means for improving vehicle fuel economy.

Stobart et al. continue advancing the control literature with their effort on regulating thermal recovery systems in 2007 [63]. The lower manufacturing costs and high exhaust temperatures lead the authors to prefer spark ignition engines to compression ignition engines for vehicle implementation. Separation of thermal recovery from work production with a pressurized accumulator and hybrid architecture combat the unsteady waste heat conditions, improving controllability. Heating times for the 50 kW engine example, achieving heat recovery with a steam Rankine cycle featuring an accumulator, ranges from about three to four min. Reduced heating times are achieved with smaller water volumes and after short stops. Of the expander options, reciprocating expanders are relatively efficient and simple to control.

Concurrently in 2007, Lemort et al. presents an experimentally validated numerical model of an ORC using HCFC-123 as the working fluid [64]. This effort links individual sub-models of each Rankine cycle component in order to create an overall model, allowing optimization of the cycle operating conditions for maximum performance. They utilize a scroll expander sub-model from a previously published work [65] that uses steam as the working fluid. As a result, the model requires recalibration of certain parameters for HCFC-123. Heat enters the cycle from two hot air streams (177–189 °C and 137–160 °C) in an amount around 15 kW, while converting between 0.7 and 1.0 kW into mechanical power. Experimental data from 13 tests is presented for comparison with simulations, validating the accuracy of the global cycle model. The authors' model is shown to agree relatively well with experimental measurements in spite of involving a limited number of parameters.

In what continues as a busy year, Quoilin describes experimental results and optimization of a small scale ORC through simulations of a validated computer model [66]. After considering numerous prospective working fluids, selection of an isentropic fluid (R-123) happens because of its efficient operation with source temperatures between 100 and 200 °C. The authors present a schematic of their ORC test bench, which utilizes a scroll expander modified from a scroll compressor. Achieving maximum WHR potential of the system occurs by varying certain parameters such as the hot air source temperature, expander rotational speed, and refrigerant charge. Results demonstrate maximum cycle efficiency of 7.4%, while simulations accounting for recommended modifications predict a further efficiency gain up to 11.58%.

This same year, Kadota and Yamamoto develop a transient bench for simulation of Honda vehicles with various power-train configurations [3]. Among the simulated power plants were conventional IC engines, hybrid electric (HE), and HE with a steam ORC for WHR. Schematics in the paper present the components utilized in each model, which the researchers validated experimentally in an individual manner before evaluating system performance over a full driving cycle. The HE system with WHR demonstrates a 6.1% thermal efficiency improvement in the Japanese 10–15 mode. Fuel economy predictions were within ± 1 percent of measured values.

In 2009, Ringler et al. investigate the use of an ORC on a four-cylinder engine for WHR [67]. They examine system performance as a function of heat recovery from exhaust only (system A) and exhaust + engine coolant (system B). Results from this effort determine that water was the most appropriate fluid for system A while an alcohol (e.g. ethanol) was best for system B due to a lower temperature heat addition. To predict additional performance, simulations using a Dymola modeling tool examine the different systems with A having better performance when vehicle speeds exceed approximately 65 mph. Alternatively, system B demonstrates a higher potential for typical driving between 45 and 70 miles per hour, resulting in an engine performance increase in the range of 10%.

Use of an ORC to recover waste heat from a high pressure ratio gas turbine studied by Chacartegui et al. is also accomplished in 2009 [68]. While the heat recovery is not achieved using an ICE as the power plant, the gas turbine exhaust temperature is comparable, making the results applicable to the current effort. Furthermore, this work is included because it compares the six potential working fluids of R113, R245, isobutene, toluene, cyclohexane, and isopentane. Parametric optimization of the ORC, along with several commercial gas turbines, is used to predict the overall system performance. Of the fluids, cyclohexane and toluene provide the highest global efficiencies, with comparable system costs.

That same year, a comparative study of four potential methods for waste heat recovery in cement plants is done by Wang et al. [28]. Two sources are used to power the thermodynamic cycles, the preheater (340 °C) and clinker cooler (320 °C), both resembling the low end of ICE exhaust temperatures. The systems evaluated are single flash steam cycle, dual pressure steam cycle, ORC, and Kalina cycle. An exergy analysis is examined with genetic algorithm parameter optimization for each candidate, resulting in the conclusion that the Kalina cycle would achieve the best performance. For comparison, the ORC achieved 20.9% efficiency while the more complex Kalina cycle provided 24.1%.

In 2010, Srinivasan et al. examine the waste heat recovery potential of an ORC for improving the efficiency of a high-efficiency, low-emissions dual fuel Low Temperature Combustion (LTC) engine [69]. The authors' single-cylinder test engine uses Advanced Low Pilot Ignited Natural Gas (ALPING) LTC, where pilot diesel sprays mix with surrounding natural gas prior to combustion. Simulations using exergy and pinch-point analysis, along with measured engine exhaust parameters, predict Fuel Conversion Efficiency (FCE) and emissions improvements. Different injection timing, engine load, and EGR percentages are used to find results for a range of engine operation. On average, an R113 working-fluid based ORC improved FCE by 7% while reducing NO_x and CO₂ emissions by 18%. Since R113 is a dry fluid, the authors achieve the optimum efficiency by evaporating to the saturated vapor curve, avoiding superheat.

Concurrently, Mohd et al. describe their low power output (<1 kW) ORC for energy generation from low temperature waste heat [70]. This work experimentally evaluates heat sources ranging from 60 to 100 °C and cold source temperatures between 10 and 30 °C. The authors choose HFC-245a as the working fluid for the

cycle, while selecting a rotary-vane type expander in order to minimize system costs. Laboratory test results reveal a maximum thermal efficiency of 3.82% for an 80 °C temperature difference and an expander efficiency of 40%.

Additionally in this year, Espinosa et al. discuss the optimal ORC configuration for WHR on commercial trucks [71]. This work considers heat sources from the CAC, engine coolant, EGR, and exhaust gases. They mention that exhaust gases are the most practical waste heat source since simultaneous WHR from both EGR and the exhaust line adds complexity and increases cost. Moreover, the energy available in engine coolant is of low quality. The authors prefer using the ram air speed from vehicle motion in order to cool the ORC condenser since the power consumption of a fan would increase with the square of the required airflow rate. This work uses computer models to evaluate water, ethanol, and HFC-R245fa with the latter chosen as the most appropriate working fluid. The high global warming potential of HFC-245fa suggests an HFO fluid with higher critical temperature than HFO-1234yf could be promising in future Rankine cycles. Finally, they simulate the different ORC configurations using zero-dimensional and one-dimensional simulation models. The zero-dimensional model uses isentropic efficiencies and three-zone heat exchangers; whereas, the one-dimensional model comes from the commercial engine simulation program GT-POWER.

Meanwhile, three possible ORC configurations are considered by Vaja and Gambaratta in 2010 in order to recover waste heat from a 12 cylinder supercharged natural gas engine [72]. These candidates are a simple ORC using exhaust gas, a simple cycle using exhaust and coolant, and a regenerated cycle. Each of the three typical classes of working fluids are represented by benzene (dry), R11 (isentropic), and R134 (wet). Environmental and safety concerns are recognized in the paper; however, the authors conclude their results only based on thermodynamic attributes. The regenerative cycle, as well as the simple cycle using both exhaust and coolant waste heat along with benzene as the working fluid, provided the highest efficiency improvements over the engine rated value at around 12.5%. However, the simple cycle using just exhaust energy and benzene has a comparable efficiency of 11.4%. As a result, the designer must weigh a slight drop in efficiency against a reduction in initial cost and complexity. R11 was noted as the next most attractive fluid, with efficiency increases around 10% for both simple cycles.

A further effort by Yamada et al. in 2010 describes a unique Rankine cycle configuration for WHR from a hydrogen ICE [73]. The authors propose an open Rankine cycle that discharges the working fluid to the atmosphere after expansion. In this system, a water separator recovers water from the exhaust pipe that passes through a filter and subsequently through the pump, indicating the start of the cycle. A modified exhaust manifold acts as the cycle evaporator, followed by an expander. The cycle was simulated with and without a condenser, leading to the conclusion that the condenser was not cost-effective. Inclusion of the open Rankine cycle without a condenser provides thermal efficiency improvements over the hydrogen ICE of 2.9–3.7% at various engine speeds.

A clear example of the progress toward efficient and economical small ORC's is presented by Quoilin et al. in the same year [74]. This work describes a semi-empirical model of an ORC using the refrigerant HCFC-123 along with a previously validated scroll expander model. By modifying a mass produced, oil-free open-drive scroll compressor to operate as an expander, the authors limit system cost while achieving heat recovery efficiency equal to 9.9%. This was accomplished after optimizing cycle parameters while generating power from two low temperature sources.

In what continues to mark a busy year, Weerasinghe et al. compare Rankine cycle WHR with turbo-compounding as methods

to boost the thermal efficiency of diesel engines [75]. In effect, turbo-compounding directly expands exhaust gases in a turbine for power generation, representing part of a Brayton cycle. An interesting aspect of the Rankine cycle is the steam storage reservoir between the evaporator and expander, which provides an energy buffer through periods of high-load or low-load engine operation. While water is chosen as the cycle working fluid, the authors note that further advancements in steam expanders are underway at the University of Sussex. A Matlab based model using the QSS Toolbox simulates both systems over the US Federal Heavy Duty Transient Test Cycle, resulting in a fuel economy improvement of 20% or more with the Rankine cycle and only around a 2.5% savings from turbo-compounding.

One year later, the performance of an ORC using R-12, R-123, R-134a, and R-717 is parametrically optimized by Roy et al. [76]. Both a constant heat source temperature of 550 K and a variable heat source are considered in the study. In each case, R-123 produces the maximum efficiency ($\sim 19\%$) and lowest irreversibility of the candidate fluids. Along with the thermodynamic analysis of each fluid using Matlab, environmental concerns are presented with respect to the Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) of the refrigerants. They indicate that ammonia (R-717) has zero impact on ODP and GWP, while R-12 (a chlorofluorocarbon: CFC) contributes to global warming and continually destroys ozone for up to two years. Furthermore, the HCFC studied (R-123) has both a low ODP and GWP; whereas, R-134a (a hydrofluorocarbon: HFC) does not have any ODP but has a high GWP.

While most authors are designing for maximum ORC efficiency, Quoilin et al. also consider the system size and cost in a paper published in the same year [77]. These criteria are used in a thermo-economic optimization using six working fluids: R245fa, R123, n-butane, n-pentane, R1234yf, and Solkatherm. Economic considerations find a different optimal design than a purely thermodynamic analysis. This is due in part to the high efficiencies that result from the use of high critical temperature working fluids, which improve performance at the cost of increased component sizes required for low specific vapor densities. The economic optimum working fluid in their study is n-butane at the specific cost of 2136€/kW that results in an efficiency of 4.47%, below the thermodynamic maximum of 5.22%.

A valuable review of Rankine cycle thermal Exhaust Heat Recovery (EHR) is authored by Wang et al. in 2011 [78]. EHR is a sub-category of WHR limited to recovering heat at temperature levels provided by ICE exhaust, similar to the range of interest in this review. This work illustrates the diversity of research efforts in this area, along with the potential of EHR systems to improve overall powertrain efficiency. In comparison to Wang et al.'s effort, this paper provides historical context, practical cycle design considerations along with system and modeling descriptions while highlighting additional literature in this area. As a result, the combination of this effort with Wang et al.'s review provides a nearly complete summary of research in this important area.

While the authors provide insight on working fluid and expander selection considerations, the length of the work prevents a detailed description of each study. Moreover, their efforts do not draw any definitive conclusions, as this manuscript will accomplish in the following section. However, briefly summarized here, their paper states that reciprocating expanders are preferred for locomotives, ships, and stationary engines, despite having a lower level of technical maturity. In addition, applications featuring conversion of mechanical to electrical energy favor turbines, while the rotational speeds of reciprocating expanders allow direct use of mechanical work. Working fluid selection is crucial for efficient EHR and achievement of high cycle efficiencies. Water's high stability

temperature and evaporation enthalpy provide the maximum power but requires high boiler pressures, low condensing pressures, and a high degree of superheating. They find that implementing a Rankine cycle on heavy-duty applications can increase the total powertrain efficiency by up to 30% based on the NEDC driving cycle. They state that while developments in EHR have rapidly progressed over the past decade, attempts to apply EHR to production vehicles must continue moving forward in order to ensure meeting future fuel economy and emission standards. This requires demonstration of efficient thermal EHR and precise control with small hardware.

Just recently, Bianchi and De Pascale evaluated three thermodynamic cycles in order to recover low and medium grade waste heat [22]. These cycles are the ORC, Stirling, and the inverted Brayton; of which they resolve that an ORC is the most attractive of the candidates. Four organic fluids (R133a, R245fa, iso-butane, and benzene) were considered for the ORC, with benzene achieving the highest efficiency at around 20%.

2.1. Review summary

Growing concerns over air pollution and escalating fuel prices through the 1970's resulted in attempts to find viable alternatives to the IC engine. However, the low power density, high cost, and low efficiency of other power cycles, prevented a substantial change in vehicle propulsion. Instead, the focus narrowed to WHR systems in order to increase efficiency through cogeneration by supplementing the engine's power by means of converting thermal energy into a more useful form; either mechanical or electrical. Several efforts resulted in systems that increase the IC engine's efficiency; however, decreasing fuel prices in the 1980's and improved engine designs stalled implementation of the WHR architecture.

Recent published works sponsored by Honda, Toyota, Wartsila, BMW, and Volvo show a renewed interest in WHR in order to increase the thermal efficiency of ICE's [1,3,47,53,67,71]. Motivating this resurgence is escalating fuel prices and future CO₂ emission regulations. In addition, these systems are becoming more viable due to recent technological advancements that have increased the efficiencies of individual components within WHR systems. Among these improvements are smaller expander internal leakage areas [66] and improved rotor profiles [57], along with more efficient heat exchangers [1].

The historical review of the last section indicates that the majority of WHR researchers prefer steam Rankine systems or ORC's instead of Brayton, Stirling, Kalina, and supercritical CO₂ thermodynamic cycles along with being favored over thermoelectric devices. This is because Rankine cycle systems offer the most attractive combination of simplicity, component cost, and efficiency. For each intended application, the additional expenditure and complexity associated with incorporation of preheating with engine coolant waste heat or a recuperator (e.g. additional hardware) above the traditional Rankine cycle should be weighed against the resulting efficiency gains. No configuration is optimal for every waste heat source; hence, a thermodynamic analysis targeting the specific source must be conducted first.

A review of the literature demonstrates that selection of the working fluid and expander has a significant influence on the efficiency of the WHR system. Most applications achieve the highest ORC efficiencies using nearly isentropic and high critical temperature working fluids. However, these criteria fail to address numerous practical design conditions, such as operating pressures, component sizes, expander rotational speeds, expansion ratios, and environmental concerns. Thus, the space available onboard mobile waste heat sources should be determined prior to cycle design. In addition, further costs incurred from utilizing exceedingly high or

low pressures at specific states of the cycle to promote efficiency must be justified. For instance, greater thermal efficiencies are achievable through higher evaporation pressures; however, this adds expense to the system in order to handle these high pressures [79].

Environmental concerns negate the use of many of the fluids discussed in early works. As a result, ORC systems should only utilize working fluids with low Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) [76]. Natural refrigerants or hydrocarbons are preferred, while HCFC's and HFC's provide fewer negative effects than CFC's [76]. Organic fluids and water lead to similar efficiencies in the range of normal engine exhaust temperature levels; however, organic fluids are favored at low temperatures and water is preferred as the source temperature increases. While water often yields a more efficient WHR process at these higher temperatures, condensing pressures below atmospheric pressure and wet expander exit conditions are common deterrents to their usage. In addition, water requires high expansion ratios that may not be met with reciprocating expanders or single-stage turbines and freezing occurs with low ambient temperatures.

Previous works have shown that turbines are superior for high temperature and high output WHR systems, while reciprocating expanders are preferred for small applications. Turbines generally provide higher efficiencies than reciprocating devices, but the aforementioned technological advancements have narrowed this disparity. In addition, turbines do have a higher initial cost, which is offset slightly by additional fuel savings through this increased efficiency. Of interest, practical advantages of reciprocating expanders such as lower rotational speeds, potential hermetic power generation, and decreased sensitivity to wet expander outlet conditions should be considered when choosing an option for the expansion process. Reciprocating expanders are also more controllable with respect to fluctuating waste heat conditions. Early efforts couple system expanders to output shafts with speed reduction gearboxes, while later work targets hybrid vehicles as to decouple energy recovery from usage. Belt systems link some reciprocating expanders to output shafts; however, turbine rotational speeds prevent this configuration.

A large portion of potential engine WHR applications are mobile vehicles, such as passenger cars and long-haul trucks. Since the space available for the ORC system is limited, low volumetric flow fluids and compact heat exchangers are desirable. It is possible to adjust for small heat exchanger size using forced convection, which can be achieved by exposing the condenser to ram-air or using a fan-equipped condenser. However, component size may be limited by selecting a working fluid with desirable heat transfer characteristics, as described by Lee [80]. With respect to pumping the working fluid throughout the cycle, the high fluid temperatures achieved tend to favor the use of diaphragm-type pumps. This is because they are designed to operate at high pressures and low flow rates, typically encountered for high ORC efficiency designs in small applications such as ICE WHR.

The largest portions of waste heat from internal combustion engines are lost through the high- and medium-temperature engine exhaust and coolant, respectively. Studies show that the higher exergy level of engine exhaust allows more efficient heat recovery; however, preheating a WHR system's working fluid using engine coolant energy can also be desirable [51,56]. Selection of the optimal working fluid for a specific application requires WHR system models that are capable of comparing cycle performance using different fluids. The fluids with the highest critical temperature often appear the most desirable from a first law point of view, but practical and economic considerations should also receive attention.

Since these models often neglect heat transfer to the environment along with mechanical losses, actual WHR systems rarely achieve the performance suggested by idealized computer models. As a result, physical experiments often produce roughly half the power of the idealized WHR. On average, optimistic simulations forecast ORC efficiencies between 15 and 20%, while realistic expectations lie in the range of 7–10%. Thus, since engine efficiencies are similar to exhaust waste heat fractions, fuel economy improvements around 10% are a feasible outcome.

Direct predictions of fuel economy improvements must account for a slightly reduced engine performance caused by the additional exhaust backpressure imposed. In particular, horsepower losses of 1.5–2.5% at high loads and 0.2–0.5% at low loads have been found [4]. In addition, the powertrain efficiency gain only begins after sufficient heat is transferred to the working fluid, which requires approximately three to four min in the presence of an accumulator [63]. Systems without accumulators achieve reduced heating times, providing a larger reduction of emissions and fuel consumption under cold start driving cycle assessments. Most efforts locate waste heat recovery equipment downstream of catalytic devices. In this configuration, carbon dioxide emissions drop in proportion to fuel consumption, with marginal effects on emissions during engine warm up. Alternatively, combined evaporator/catalyst devices and upstream evaporators suffer from prolonged startup emissions, lessening the emissions advantage of ORC WHR systems.

Research suggests a properly designed ORC for WHR of engine exhaust can reduce emissions and pay for itself through fuel savings within a relatively short amount of time (approximately 2–5 years), primarily depending on annual travel. Hence, the system can help achieve future emission standards while reducing operating costs. Construction of a model that couples a virtual engine to a WHR system allows quantification of these advantages, while simultaneously meeting any packaging constraints or initial investment restrictions. To achieve the maximum ORC performance, parametric studies of operating variables (pump speed, expander load, etc.) should be conducted to yield the highest power. At the same time, second law analysis reveals where the largest amounts of exergy destruction are occurring. Going further, the ORC can be optimized from an economic perspective, determining the configuration that gives the highest fuel savings over a specified period of time [77].

3. Conclusion

A review of the open literature with respect to WHR finds that IC engine exhaust contains heat with sufficient exergy to justify implementation of a secondary cycle. Among the different cycles, ORC's are the most commonly implemented WHR systems in order to generate power from low-grade to medium-grade waste heat. This is because Rankine systems use standard components and operate efficiently using these grades of energy. Turbomachines are preferred for large output systems while displacement-type expanders dominate small-scale efforts. Finally, no single working fluid is best for all ORC's as the selection of the proper working fluid requires consideration of operating conditions, environmental concerns and economic factors.

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